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Experimental Fire Tower Studies on Mechanical Pressurization to Control Smoke Movement Caused by Fire Pressures

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Résumé

Pour concevoir un système mécanique de limitation de la propagation de la fumée destiné à protéger les voies de sortie, il faut disposer d'informations concernant les écarts de pression défavorables causés par les divers facteurs en cause, et concernant le niveau de mise en pression mécanique nécessaire pour les contrer. Cet exposé porte sur les écarts de pression causés à la fois par la poussée et par l'expansion thermique dues au feu. Les essais ont été réalisés dans la tour de dix étages servant aux expériences d'incendies, dans le cadre d'un projet portant sur la mise au point de techniques de limitation de la propagation de la fumée visant à rendre les ascenseurs utilisables en cas d'incendie. Les valeurs calculées des écarts de pression défavorables causés par la poussée, de part et d'autre des parois de la cage d'ascenseur, concordaient généralement avec les valeurs mesurées, pour des températures d'incendie allant de 450 à 850 °C. De même, les quantités minimales de mise en pression mécanique nécessaires à la neutralisation étaient égales aux pressions défavorables causées par la poussée. Les pressions défavorables causées par l'expansion thermique due à l'élévation rapide de la température ont été déterminées les exutoires de façades en position fermée et en position ouverte. Les résultats des essais ont permis d'établir que les pressions défavorables causées par le feu peuvent être contrôlées grâce à la mise en pression mécanique de manière à empêcher la contamination, par la fumée, des espaces protégés. Il faut mettre en marche dès que possible le système de mise en pression mécanique, car le temps de purge d'une cage ou d'un hall d'ascenseur contaminé peut être long.

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ABSTRACT

In designing a mechanical smoke control system to protect escape routes, it is necessary to have information on the adverse pressure differences caused by the various mechanisms and on the level of mechanical pressurization needed to overcome them. This paper deals with pressure differences caused by both the buoyancy force and thermal expansion due to fire. The tests were conducted in the ten-storey experimental fire tower in conjunction with a project on smoke control technology for a fire safe elevator. The calculated values of adverse pressure differences across the elevator shaft walls caused by the buoyancy force agreed well with the measured values, for fire temperatures from 450 to 850°C. Also, the minimum amounts of mechanical pressurization required for neutralization were equal to the adverse pressures caused by the buoyancy force. Those caused by thermal expansion due to the rapid temperature rise were determined with the outside wall vents closed and with them opened. The test results verified that adverse pressures caused by fire can be controlled by mechanical pressurization to prevent smoke contamination of protected spaces. The mechanical pressurization system should be operated as soon as possible as the purging time for a contaminated elevator shaft or lobby can be long.

INTRODUCTION

The performance requirement for most mechanical smoke control systems is to control pressures in a building so that smoke is prevented from entering escape routes, such as an elevator shaft or stairshaft. In designing such systems, a knowledge of the adverse pressure differences caused by the fire and other mechanisms is needed to determine the amount of pressurization or exhaust required to overcome them. The mechanisms that should be considered are the temperature effect of fire, stack action due to the difference in air temperature inside and outside a building, wind action, and the operation of mechanical ventilation systems. The maximum adverse pressure difference due to a combination of these mechanisms can then serve as a criterion for designing a smoke control system and for testing its performance in a building.

The adverse pressures caused by these mechanisms were investigated in the ten-storey experimental fire tower, as part of a joint project

being conducted by the National Research Council of Canada and the National Bureau of Standards (USA) on developing smoke control technology for a fire safe elevator (1). This paper reports on the results of tests conducted to determine the adverse pressures caused by buoyancy and thermal expansion due to fire, and the amount of mechanical pressurization required to prevent smoke from entering the elevator shaft and elevator lobbies.

TEMPERATURE EFFECT OF FIRE

Heat generated by fire results in increased gas temperature. Assuming that a fire compartment leaks sufficiently to preclude an appreciable buildup of pressure, it follows from the gas law, that the gas volume increases approximately in proportion to its absolute temperature. The pressure developed by the outflowing gas depends on the leakage area and volume of the fire compartment and on the rate of temperature rise. When the fire temperature reaches a steady value, the gas is no longer expanding and the smoke moves out of the compartment by buoyancy force alone. With fire in one floor of a building, air flows in through leakage openings in the walls of the fire compartment at low levels and smoke flows out of the compartment at upper levels to adjacent areas. This paper deals with a fire in a compartment of one-storey height, not in a large space such as an atrium. The pressure difference due to buoyancy between a fire compartment and its surroundings can be expressed by the following equation:

$$\Delta P_f = gh\ (\rho_i - \rho_f) = gh\rho_f\ (T_f - T_i)/T_i \qquad (1)$$

where

ΔP = pressure difference, Pa
g = gravitational constant, m/s^2
h = distance from the neutral pressure level, m
ρ = gas density, kg/m^3
T = temperature, K

Subscripts

i = outside the fire compartment
f = fire.

The level where the pressures of the fire compartment and the surrounding areas are equal is called the neutral pressure level (NPL). Above this level the pressures in the fire compartment are greater than those outside the compartment, resulting in gas flow out of the fire compartment; conversely, below this level air flows into the fire compartment. The location of the neutral pressure level depends on the vertical distribution and size of leakage openings and on the temperature of gases in the fire compartment and the surrounding area. It occurs on a level which results in a balance of mass flow into and out of the fire compartment.

DESCRIPTION OF THE EXPERIMENTAL FIRE TOWER

The fire tower (1) is part of the experimental facilities of the National Fire Laboratory of the National Research Council of Canada, and

is located about 60 km west of Ottawa. The plan view of a typical floor is shown in Figure 1. The experimental tower contains all the shafts and other features necessary to simulate the air and smoke movement patterns of a typical multi-storey building, including the elevator, stair, smoke exhaust, service, supply, and return air shafts. The exterior walls and the walls of vertical shafts are provided with variable openings that can be set to simulate the leakage areas of typical buildings. Two propane gas burner sets, each capable of producing heat at a rate of 2.5 MW, are located on the second floor burn area.

A separate structure adjacent to the tower houses the air moving and heating plant of the experimental tower; the air ducts run underground through a short tunnel to the bottom of the experimental fire tower. One system handles the main air supply and heating load and the other supplies outside air, either to the experimental stair and elevator shafts, or to vestibules interposed between the entrances to these shafts and the burn area.

Temperatures are measured in ten different locations on each floor using chrome-alumel thermocouples. Pressure differences across the various walls are measured using eighteen static pressure taps mounted flush to the walls on each floor. All pressure lines are connected to a 24-port pressure switch equipped with a diaphragm-type magnetic reluctance pressure transducer and located on the same floor in the observation area. Carbon dioxide concentrations are measured at six locations on each floor in the shafts, lobbies, corridors, and burn area by copper sampling tubes connected to a 12-port sampling switch unit with a nondispersive infrared gas analyzer. All devices of the three systems are controlled and monitored by a computer-based data acquisition and control system in the attached services unit.

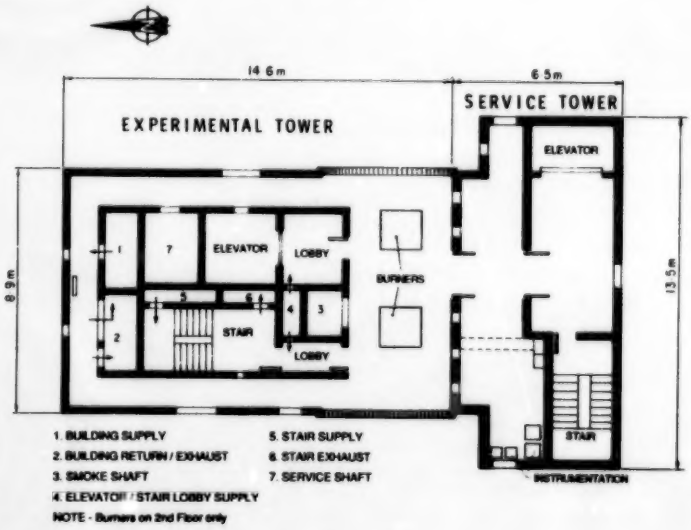

FIGURE 1. Plan of the experimental fire tower.

TEST PROCEDURE

The leakage areas of the experimental fire tower were set for a building with average air tightness and an area per floor of 900 m^2 or seven times that of the floor area of the experimental tower (1). They were based on measurements in several multi-storey buildings (2,3).

The fire tests were conducted using the propane gas burner on the second floor nearest the elevator shaft (Figure 1) with the temperature near the ceiling above the burners to follow close to the ASTM-E119 standard time-temperature curve up to the maximum test temperatures and held constant thereafter. In addition to the pressures recorded throughout the tower with the data acquisition system, pressure differences across the elevator lobby wall on the door side at the 0.40, 1.93 and 3.08 m levels of the second floor were recorded continuously with a pen recorder.

Five minutes after ignition, the east and west wall vents on the second floor, each with an area of 0.46 m^2, were opened to simulate broken windows. Thirty minutes after ignition, the pressurization fan for the elevator shaft was activated and the supply air rate adjusted to neutralize the adverse pressure difference across the elevator lobby wall measured at the 3.08 m level on the fire floor (second floor). After the test, with the tower back to normal temperature, the elevator shaft was pressurized at the same supply air rate to record the pressure difference across the lobby wall at the same level. Six such burn tests were conducted at fire temperatures of 450, 550, 660, 750, and 840°C. They were conducted with temperature differences between inside and outside the tower of less than 6°K and wind speed of less than 16 km/h.

To investigate the adverse pressures caused by thermal expansion, both the elevator lobby pressure difference at the 3.08 m level and the burn temperature were recorded on a continuous pen recorder during the temperature rise from the time of ignition of the gas burner. The measurements were repeated with two outside wall vents (total area of 0.93 m^2) opened prior to igniting the burner.

Two fire tests were conducted at 750°C with the elevator shaft pressurized; in the first, the elevator shaft was pressurized before ignition and in the second, it was pressurized 50 minutes into the burn period. For both tests the elevator shaft was pressurized to obtain a pressure difference across the elevator lobby wall of 25 Pa under non-fire condition. The value of 25 Pa is often used in designing smoke control systems to combat fire pressures in buildings. Pressure differences, temperatures, and CO_2 concentrations were measured throughout the tower during the tests.

RESULTS AND DISCUSSION

Buoyancy Force

Pressure differences across the walls of the elevator lobby and the elevator shaft at the 3.08 m level on the fire floor (second floor) both referenced to the burn area pressure for fire temperatures from 450 to 840°C are shown in Figure 2. They varied from 9 to 14 Pa for the elevator shaft wall and from 5 to 7 Pa for the elevator lobby wall. The differences were smaller for the lobby wall because the elevator wall

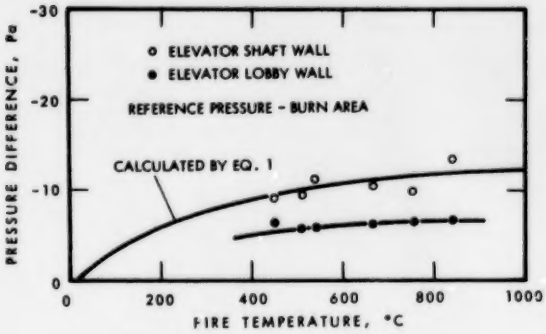

FIGURE 2. Pressure difference across elevator shaft wall and elevator lobby wall for various fire temperatures (pressure differences measured 3.08 m above 2nd floor level).

containing the elevator door provided additional resistance to gas flow from the burn area to the elevator shaft, and because the temperature was higher (54°C) in the lobby than in the shaft (23°C). The neutral pressure levels were located at about 1.7 m above floor level based on the pressure difference measurements on the door side of the elevator lobby wall. Using this value, pressure differences across the elevator shaft wall were calculated using Equation 1; they agreed reasonably well with the measured values, as shown in Figure 2.

The maximum measured value was 14 Pa. Fang (4) has measured pressures caused by room fires during a series of full-scale tests in a room with an open doorway and a ceiling height of 2.4 m. The maximum pressure difference reached was 15 Pa, across the burn room wall at the ceiling, measured shortly after flashover. DeCicco (5) reported adverse pressure differences in the order of 10 to 15 Pa and a sharp peak of 35 Pa four minutes after ignition from a full scale fire test in a room with a floor height of 3.5 m in a multi-storey building. Butcher et al. (6) reported an adverse pressure difference of 5 Pa at the top of a stair door with a wood crib fire at 1000°C. About 15 Pa appears to be the expected fire pressure due to buoyancy for ceiling heights up to 3.5 m. As the fire pressure varies directly with the distance from the neutral pressure level (Eq. 1), higher pressures can be expected for floors of greater ceiling height.

During each fire test the elevator shaft was pressurized to neutralize the adverse pressure difference across the elevator lobby wall at the 3.08 m level. Figure 3 shows the vertical pressure difference profile with the fire temperature at 750°C. Without pressurization the neutral pressure level was located at the 1.7 m level; with pressurization it was raised to the 3.08 m level, with an accompanying shift in the pressure profile to the right in the area of positive pressures.

The supply air rates for pressurization required to neutralize the adverse pressures for the range of fire temperatures tested were from 800 to 900 L/s for the test elevator shaft. When the elevator shaft was

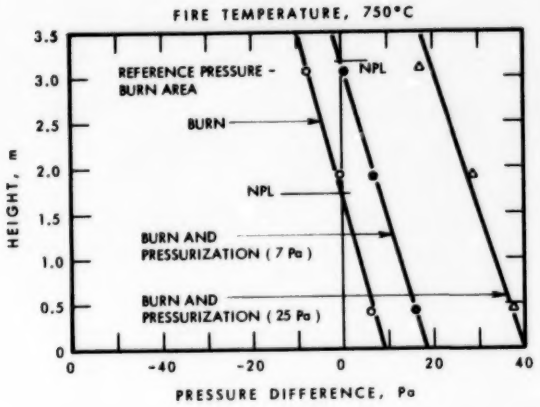

FIGURE 3. Pressure difference across the walls of the second floor elevator lobby during fire test with elevator shaft pressurization.

pressurized with these supply air rates and with the tower back to normal temperature, the amounts of pressurization were found to be about equal to the pressure differences caused by the fire. The pressurization required to prevent smoke infiltration, therefore, would be equal to the adverse pressure caused by the fire. The tests demonstrated that it is appropriate to use the adverse pressure difference due to fire as a component of the maximum required pressure difference as recommended in the ASHRAE Design Manual (7).

Thermal Expansion

The pressure differences shown in Figures 2 and 3 are those for fire temperature at a quasi-steady state. At ignition of the gas burner, as shown in Figure 4, the pressure difference increased instantaneously to a peak of 31 Pa. Immediately thereafter, it dropped sharply to 16 Pa and gradually decreased to 6 Pa when the temperature stabilized at 600°C. The cross-hatched area in Figure 4, which was obtained by subtracting the pressure differences due to buoyancy force from the measured pressure differences, represents the pressure differences due to thermal expansion. The test was repeated with the two outside wall vents (a total area of 0.93 m^2) opened before ignition of the burner. As seen in Figure 5, a sharp peak of 8 Pa occurred at ignition, followed by a pressure increase to a maximum pressure difference of 9 Pa at 0.9 min after ignition; after that it decreased gradually to 7 Pa when the temperature reached 520°C.

The area of opening in the fire floor enclosure has a significant influence on the effect of thermal expansion. The openings in the fire compartment affect the amount of pressure developed in the fire floor and the rate of temperature rise which, in turn, affects the rate of gas expansion. For buildings of typical construction, it is unlikely that the peak pressure difference caused by thermal expansion, because of its short duration, can seriously affect the performance of a smoke control system. However, it can be substantial for a relatively airtight

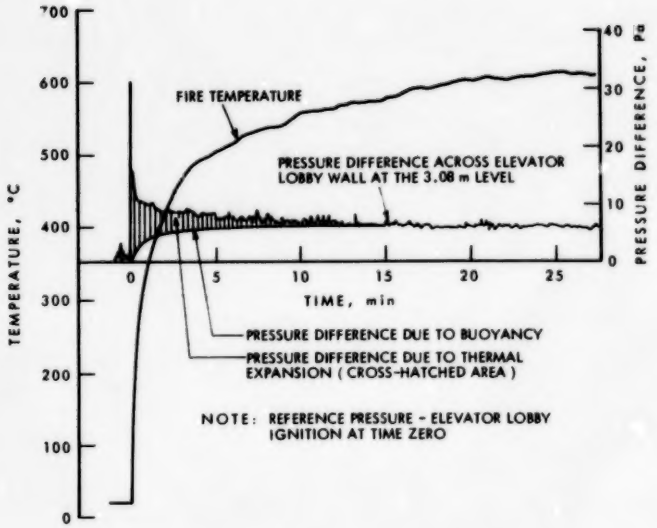
TEMPERATURE, °C
PRESSURE DIFFERENCE, Pa
FIRE TEMPERATURE
PRESSURE DIFFERENCE ACROSS ELEVATOR LOBBY WALL AT THE 3.08 m LEVEL
TIME, min
PRESSURE DIFFERENCE DUE TO BUOYANCY
PRESSURE DIFFERENCE DUE TO THERMAL EXPANSION (CROSS-HATCHED AREA)
NOTE: REFERENCE PRESSURE - ELEVATOR LOBBY IGNITION AT TIME ZERO

FIGURE 4. Pressure difference across elevator lobby wall and fire temperature vs time - outside wall vents closed.

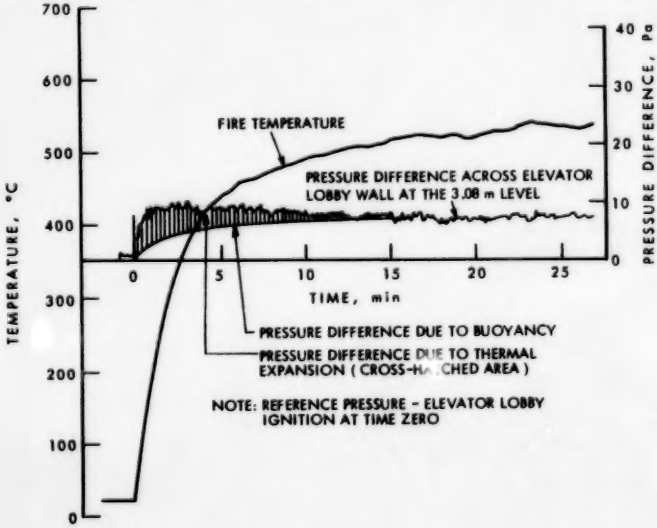
TEMPERATURE, °C
PRESSURE DIFFERENCE, Pa
FIRE TEMPERATURE
PRESSURE DIFFERENCE ACROSS ELEVATOR LOBBY WALL AT THE 3.08 m LEVEL
TIME, min
PRESSURE DIFFERENCE DUE TO BUOYANCY
PRESSURE DIFFERENCE DUE TO THERMAL EXPANSION (CROSS-HATCHED AREA)
NOTE: REFERENCE PRESSURE - ELEVATOR LOBBY IGNITION AT TIME ZERO

FIGURE 5. Pressure difference across elevator lobby wall and fire temperature vs time - outside wall vents open.

compartment such as a bank vault or a ship compartment; pressure relief vents should be provided for such cases.

Elevator Shaft Pressurization and Smoke Concentrations

The vertical profile of pressure difference across the elevator lobby wall during the burn period with pressurization is shown in Figure 3. The required outside supply air rate for pressurization was 1880 L/s. The concentrations of CO_2 as surrogate indicator of smoke can be expressed as percentage of concentration in the fire floor (second floor) measured 0.3 m below the ceiling in the burn area. Although a detailed hazard analysis is beyond the scope of this paper, a simplified approach to the smoke obscuration problem assumes that particulate concentrations from a solid fuel fire would be proportional to the CO_2 concentrations measured from these tests. From a consideration of smoke obscuration, an area is assumed to be reasonably safe if it is not contaminated to an extent greater than 1% of that in the vicinity of a fire area (8). This assumption is probably conservative, in that smoke deposition reduces particulate concentration.

The CO_2 concentration in the burn area was 5.2%. Without mechanical pressurization, the CO_2 concentrations (expressed in percent concentration of that in the burn area) were well above the 1% level in all spaces except the ground floor elevator lobby. Examination of the flow pattern as inferred from the pressure difference readings indicated that the combustion products spread from the burn area into the leakage openings in the walls of all vertical shafts and the ceiling of the second floor. When the elevator shaft pressurization system was activated prior to ignition, the elevator shaft and lobbies were maintained smoke free during the burn period. When it was activated during the burn period, the elevator shaft was cleared of CO_2 in a short time but the levels of CO_2 in the elevator lobbies, though much reduced, were still above the critical level. This indicated that the pressurization system should be activated before the elevator shaft and lobbies are heavily contaminated with smoke.

Although the tests were conducted in the ten-storey tower, the results are generally applicable to multi-storey buildings with typical leakage characteristics, as far as smoke movement due to fire pressures are concerned. Smoke movement due to wind and stack action was minimized by conducting tests under conditions of low wind and low inside-to-outside temperature difference.

CONCLUSION

1. The equation for calculating pressure differences due to the buoyancy force agreed reasonably well with the measured values at steady-state for the range of fire temperature from 450 to 840°C. The maximum adverse pressure difference was about 14 Pa for the elevator shaft wall and 7 Pa for the elevator lobby wall. The pressure difference due to thermal expansion can be substantial, but because of its short duration, it is unlikely to seriously affect the performance of smoke control systems in buildings of average air tightness. During this short period a substantial amount of smoke and hot gas will flow into surrounding spaces if there is no pressurization to prevent it. With a large outside wall opening such as that caused by broken windows, the peak pressure difference due to thermal expansion is considerably

less than without such openings. It should be cautioned that pressures due to thermal expansion can be substantial for relatively air-tight compartments.

2. The tests demonstrated that it is appropriate to use the adverse pressure difference due to the buoyancy force as a component of the minimum design pressure difference for designing smoke control systems for buildings.
3. The tests verified that adverse pressures caused by fire can be controlled by mechanical pressurization to prevent smoke contamination of elevators, so long as the required pressurization is maintained. The pressurization system should be operated as soon as possible, before the elevator shaft and lobbies are heavily contaminated with smoke, as the purging time can be long.

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